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SOLAR MAGNETIC FIELDS STUDY

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High resolution observations of quiet sun magnetic fields have been made at Sacramento Peak Observatory using the Lockheed Universal Filter. The existence of "salt and pepper" fields described by other observers has been called into question.

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SUMMARY

High resolution observations of quiet sun magnetic fields obtained in July 1977 at Sacramento Peak have demonstrated two facts. First, that in the quiet sun at least 85 percent of the magnetic energy in the solar photosphere resides in fields stronger than 1000 gauss. Second, that any weak fields which exist must be less than 50 gauss in strength. Also, analysis of the effects of misregistration on the appearance of magnetograms has shown that at least some of the observed "salt and pepper" fields described by Harvey and Livingston are caused by printthrough of intensity features.

INTRODUCTION

The main objective of the research has been to measure the solar magnetic field at the highest resolution currently possible in order to estimate the strength and configuration of magnetic elements. The nature of these elements is critical for solar models of mechanisms that distribute the magnetic field and for forming accurate estimates of the energy stored in the field.

The data for the strength of the quiet sun field were obtained in July, 1977 at Sacramento Peak. The quiet sun data together with the active plage data obtained a year earlier show that **the majority of the energy stored in the** field in both active and quiet regions is in the strong field.

In this report we will briefly review the active region data which have been published in Astrophysical Journal Letters (Appendix I). Then we will discuss recent results obtained from the active region data, in particular the seeing and misregistration effects on magnetic field measurements. The quiet sun data will be discussed in light of the limitations imposed by misalignment.

Finally, we will estimate the energy in active and quiet sun stored in strong and weak fields.

II. PRELIMINARY RESULTS FROM ACTIVE REGION DATA

The initial reduction of the active region magnetograms demonstrated that the field appeared to have power at spatial scales of 1/3 arc second, but that the typical scale size of the field was 1 to 2 arc seconds. In addition, the data showed that the field had a tendency to form a network with a cell size of 2-3 arc seconds.

Since we are able to detect mean fields of 100 gauss in 1/3 arc second regions, the system would have been able to detect regions with a flux as small as 6×10^{16} maxwells. This sensitivity is on the order of that of the Kitt Peak magnetograph, which regularly detects regions of 2-4 arc seconds in diameter having mean field of 5-20 gauss. The flux in these small regions are in the range from 10^{17} to a few times 10^{18} Mx. If the KPNO regions were compact, they would have appeared on our magnetograms. However, if they are diffuse they could be missed if their strength is less than 100 gauss. Given the possible errors in calibration, we estimated that the weak component of field, if it exists, was less than 500 gauss.

III. RECENT RESULTS WITH ACTIVE SUN DATA

After the initial reduction of the active region data it was decided to see how high resolution magnetograms compare with lower resolution magnetograms. Since all the magnetograms were created from digitized filtergrams taken in right (RCP) and left (LCP) circular polarized light, we applied digital smearing functions to create magnetograms of degraded resolutions. The principal result was that what appeared to be noise in the high resolution magnetograms, 1/6 to 1/2 arc second smear, persisted on the lower resolution, 1 1/2 and 2 1/2 arc second smear, magnetograms.

The phenomenon of almost all the small scale noise on high resolution magnetograms becoming signal on lower resolution magnetograms was suspect. The original magnetograms were formed by approximately aligning 5 arc second square regions of the RCP-LCP pairs. The alignment was accomplished by estimating the best alignment and then selecting from an array of magnetograms with offsets of 0, $\pm$ 1, $\pm$ 2, and $\pm$ 3 in both x and y from the best guess. The step size for the array was one digitization step of 1/6 arc second. The picture with minimum visual misalignment signal was chosen as the magnetogram.

From the above it might be expected that the final magnetogram could have a misalignment signal due to a displacement of 1/12 arc second. The intensity signal on both the RCP and LCP pairs has a RMS fluctuation of 5 percent on a spatial scale of one arc second, that is $< \Delta I/I > = 5$. Because intensity fluctuation is related to magnetic flux signal by approximately

$$\frac{\Delta I}{I} = \frac{G}{100}.$$

a displacement of 1/12 arc second should yield $\Delta I/I$ signal of .4% and thus an apparent field of 40 gauss. Since RMS fluctuations are a factor of 5 less than the peak to peak fluctuation, 200 gauss fields can be created from 1/12 arc second misalignment.

To test this hypotheses several magnetograms were formed from different RCP-LCP pairs using the above technique. Regions of apparently real field of 100 - 200 gauss again emerged on original and smeared magnetograms, but the small field in magnetograms taken by one minute of time apart were uncorrelated.

The lack of correlation on magnetograms less than a minute apart suggested that the apparent magnetic signal was in fact printthrough of the intensity gradient in the polarization pairs. Because of the random printthrough of the intensity field into the magnetic field signal an intensive study of the statistics of intensity distribution versus magnetic field was carried out. Based on our λ6302 data, the printthrough magnetic field is related to the misalignment, δ, and seeing, S, by

$$G = \frac{200\ \delta}{S}$$

where G is in gauss and δ and S are in arc seconds.

Attempts have been made to reduce the misregistration effects by extending our data set with spline fitting between data points and aligning the small subsections of polarization pairs by optimizing their cross correlation. In the quiet sun the misregistration signals can be markedly reduced by

these techniques; however, in the active sun the signal difference between the two circular polarizations is sufficiently large to affect the cross correlation and provides a fundamental limitation to the minimum detectable field strength on non-simultaneous pairs.

In spite of all the difficulties a sequence of optimally aligned strong field magnetograms has been formed, with a field detection limit of 50 gauss. This pushed our upper limit on the weak field reported in the *Astrophysical Letters* from 500 to 50 gauss.

IV Quiet Sun Data

The quiet sun data have been analyzed using the optimal alignment procedures developed for the active sun data. Based upon limited statistics the quiet sun has 1 - 3 percent of a typical arc minute square region covered with strong field. Unfortunately our data base is limited to several 2 arc minute square regions.

When attempts are made to discover diffuse field in the quiet sun, results are no more successful than similar attempts in the active sun. The unavoidable misregistration, however, does give rise to magnetograms with structures surprisingly similar to the "salt and pepper" field of Livingston and Harvey.

V Summary and Conclusions

As a result of this study we have gained considerable confidence that at least in plage regions virtually all of the magnetic energy is stored in the strong field. Even in quiet regions, assuming our observed upper limit on the weak field strength, the energy stored in strong fields is at least of the same order of magnitude as that stored in any existing weak fields. The attempt to place limits on the weak field has shown there are substantial difficulties in measuring weak fields. Thus if strong fields are formed by the concentration of weak fields, the details of the process will be difficult to discover.

Combining the results of the spectra-spectroheliograph data which show that the magnetic field strength is 1200 gauss whenever the flux is 10^{18} Mx in a arc second square region and that the regions have high field strength in one third their area with the results of this study which showed magnetic regions occur 30% over the surface in plage, we can calculate the fractional energy in strong and weak fields. It is important to note that although regions of high mean fields occupy approximately 30 percent of plage areas, comparison of flux and field strength for these regions indicate only one third of the areas of high flux have high field strengths. Therefore in plage regions the area covered by fields of 1200 gauss is only 10% total area. The energy in strong E_s, and weak, E_w, fields are proportional to

$$E_s \approx (1200)^2\,(.1) = 1.44 \times 10^5,$$

$$E_w \approx (50)^2\,(.9) = 2.25 \times 10^3$$

where we have assumed that the weak field is everywhere there is not strong field and has a value just below our detection limit. The fractional energies stored in strong and weak fields are

$$F_s = E_s / (E_s + E_w) = .985$$

$$F_w = E_w / (E_s + E_w) = .015$$

Hence, in the plage at least 98.5 percent of the magnetic energy is stored in strong field.

The results above apply to the upper photosphere. However, they can be extended upward into the transition region on the assumption that the flux in the region of strong magnetic field is uniformly expanded into the bright network structures seen in transition region lines. Reeves has measured the area of network seen in such lines to be 40% of the total area. Conservation of flux requires that

$$(1200) \times (.3) / 3 = B (.4)$$
$$B = 300.$$

So that

$$E_s \approx (300)^2 .4 = 3.6 \times 10^4$$
$$E_w \approx (50)^2 (.6) = 1.5 \times 10^3$$

and therefore

$$F_s = .96$$
$$F_w = .04.$$

Because of the rather slow spread of magnetic energy from the photosphere through the transition region, it is not likely that attempts to measure the energy gradient through photospheric lines will yield very much information.

A similar argument on the energy distribution can be carried out for the quiet sun. Here these data show 3% of the area covered by high flux regions, so

$$E_s \approx .03/3 \times (1200)^2 = 1.44 \times 10^4$$

$$E_w \approx .99\ (50)^2 = 2.48 \times 10^3$$

so

$$F_s = .85$$

$$F_w = .15$$

Therefore, even in the quiet sun the clear majority of the energy resides in the strong field.

Similar arguments can be carried out for the magnetic flux in active and quiet regions for the flux

$$\varphi_s = 1200\ (.3)\ (1/3) = 120$$

$$\varphi_w = 50\ (.9) = 45$$

and

$$F_s = .727$$

$$F_w = .273,$$

or in the active sun the majority of the flux is from strong field, but a non-negligable fraction could be from weak regions. While in quiet sun

$$\varphi_s = 1200\ (.01) = 12$$

$$\varphi_w = 50\ (.99) = 50$$

and

$$F_s = .194$$

$$F_w = .806$$

or that in the quiet sun the majority of the flux is in weak fields.

A comparison of the flux and energy estimates shows how great an error can be made if one takes magnetograph measurements which measure flux and then attempts to make inferences about the magnetic contribution to the energetics of solar processes.

APPENDIX I

THE ASTROPHYSICAL JOURNAL, 215:L41–L42, 1977 July 1

ON THE SIZE, STRUCTURE, AND STRENGTH OF THE SMALL-SCALE SOLAR MAGNETIC FIELD

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ABSTRACT

High-resolution magnetograms obtained at the Sacramento Peak Observatory place an upper limit of $\frac{1}{3}$ arcsec on the smallest magnetic field structures. These magnetograms show that the active region field is organized into roughly cellular patterns 2–3 arcsec in diameter, and that the field structures occur in the centers of "abnormal" granules. Comparison of these data and Kitt Peak magnetograms with high signal-to-noise ratio indicates there exists another component of the field that is diffuse on the scale of an arc second and has a maximum strength of less than 500 gauss.

Subject headings: Sun: granulation — Sun: magnetic fields

I. INTRODUCTION

In recent years there has been considerable controversy concerning the strength and spatial scale of solar magnetic field elements away from spots. Stenflo (1973) and Harvey, Livingston, and Slaughter (1972) inferred from magnetogram measurement in several lines that virtually all magnetic structures away from spots had a field strength of 1000–2000 gauss. Since their measurements covered a range in flux from 10^{17}–10^{19} maxwells, they inferred that the smallest elements had sizes of $0''.1$. Direct measurements of Zeeman splitting by Tarbell and Title (1976, 1977) has shown that whenever the flux is greater than 2×10^{18} maxwells in $1''.5$ resolution elements the field strength is 1400 ± 200 gauss. Their ratios of flux to field strength imply that their smallest elements have sizes between $0''.5$ and $0''.8$.

Recent new magnetogram line ratio measurements by Livingston with arc second resolution (reported by Harvey 1976) have shown that for fluxes in the range of 5×10^{16}–10^{18} maxwells a significant fraction of the elements have field strengths of less than 500 gauss.

Away from spots much of the magnetic field is organized into the familiar photospheric network. Simon and Leighton (1964) showed that the network boundary tends to surround the supergranulation flow field, and suggested that the supergranulation flow is responsible for concentrating the field into the network. This process has been very difficult to verify observationally (Smithson 1973; Worden 1976; Mosher 1976). Similarly, observers have attempted to determine whether the normal granulation organizes the field. Livingston (1968) and Simon and Zirker (1974) have failed to find any correlation between granulation and magnetic points. Our observations show that there is a definite spatial relation between the magnetic field points and the granulation pattern.

II. OBSERVATIONS

The observations were carried out on 1976 September 13 at the vacuum tower telescope at the Sacramento Peak Observatory using the Lockheed universal filter (Title 1976). The filter has a passband (FWHM) of 130 mÅ at 6300 Å. It is tunable under computer control over the range 4500–8500 Å, and can be moved in wavelength steps of 2 mÅ. The observations consisted of a series of runs in which the filter was stepped through the profile of the magnetically sensitive Fe I λ6302 line in increments of 10 mÅ. At each step, 0.25 s exposures were made sequentially in right and left circularly polarized light.

Figure 1 (Plate L2) shows such a pair taken at a wavelength 40 mÅ shortward of line center. The diameter of the field is 138″. The area shows a sunspot group (McMath 14416) in the southwest quadrant at a radius vector of approximately 0.7. The group has a well-formed preceding spot, with only a cluster of porelike spots in the following polarity (*upper left*). The preceding polarity is negative on the Mount Wilson magnetogram.

The area in the box in Figure 1 and the corresponding area in the other frame were digitized using the Lockheed PDS-1010 microdensitometer, subtracted, scaled, and played back to form a magnetogram (Fig. 2).

III. DISCUSSION

The magnetic structure shown in Figure 2 (Plate L3) consists of individual strands and elements, 1/3 to 1/2 arcsec in width. Since this is the effective seeing-limited resolution in the filtergrams, we still may not have resolved the true characteristic size of the flux ropes. However, since we believe this to be the best spatial resolution yet obtained in a magnetogram, it places a new upper limit on the directly measured scale of the field elements.

The fields in this strong plage area surrounding the spots are organized into a large cellular structure. The cells are quite similar in appearance to the familiar photospheric network found in quiet areas of the disk, although the diameters of these plage cells (20″) are only about half of the typical supergranule scale. The fields outlining the large cellular structures are in turn broken up into much smaller cell-like patterns, with

diameters of 2–3 arcsec, or approximately the scale of granulation.

It is well established that magnetic field structures are well correlated with downward flow (Frazier 1970, 1971) and that downward flow is well correlated with the granulation boundaries (Richardson and Schwarzschild 1950; Beckers and Morrison 1970). However, comparison of the magnetogram with a filtergram made in the red wing 100 mÅ from the line core shows that the magnetic field does not surround granules. Rather, the individual strong field points which comprise the magnetic cell boundaries coincide with centers of granules. However, without exception, these granules are not bright and well formed, but rather are smaller and fainter than average granules. They also have a rather fragmented appearance, similar to the "abnormal" granulation which Dunn and Zirker (1973) found in the vicinity of the solar filigree.

A time sequence of five magnetograms taken at $2\frac{1}{2}$ minute intervals was searched for temporal variations in the small cells. Clear structural evolution was seen in two of the cells, but most had not changed significantly in the 10 minute period. Since there are about 40 small magnetic cells in our field of view, the statistics are too limited to establish a cell lifetime. However, it is fair to say that the life is longer than that of granulation but shorter than that of supergranulation.

Finally, it is important to note that the magnetic fields seen in Figure 2 are entirely of one polarity. Since we are looking at the leading area of an active region, it is not surprising that one polarity is dominant. However, magnetograms of high signal-to-noise ratio made with the 512 channel vacuum magnetograph at the Kitt Peak National Observatory always show small bipolar regions scattered among the dominant field structures (Livingston and Harvey 1975), and there is no trace of these bipolar elements in Figure 2. The KPNO magnetograms show these bipolar features as having 1–3 arcsec diameters and total fluxes of 5×10^{16} maxwells or greater (Livingston, private communication). Our limit of detectability is 50–100 gauss averaged over the 1/3 arcsec resolution area, which corresponds to a flux of $3\text{–}5 \times 10^{16}$ maxwells. If these bipolar elements were composed of compact flux tubes with field strengths of several hundred gauss or higher, they should be easily visible in our magnetogram. Since they are absent, we must conclude that at least some of the magnetic structures are diffuse compared to 1/3 arcsec and have field strengths less than 500 gauss.

Drs. Richard Dunn and Jacques Beckers were instrumental in arranging our observing run and provided advice on the optical systems available for use. Drs. John Leibacher, John Harvey, and Ted Tarbell provided many useful discussions. Support for this program was provided by NASA through NAS8-30628 and by AFCRL through contract F19628-76-C00044.

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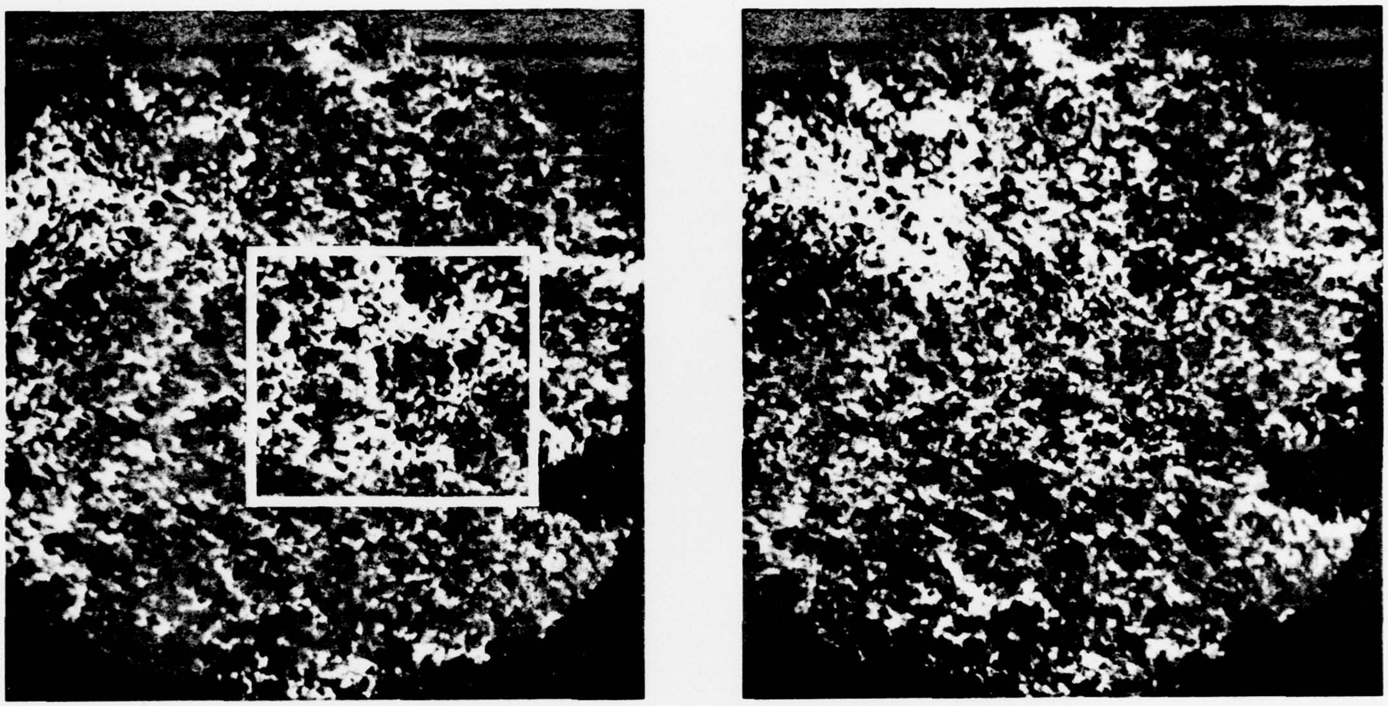

A B

Fig. 1.—Filtergram pair taken in right and left circularly polarized light in Fe I 6302 −0.04 Å. The diameter of the field is 138″. The box in frame A outlines the area from which the magnetogram (Fig. 2) was made.

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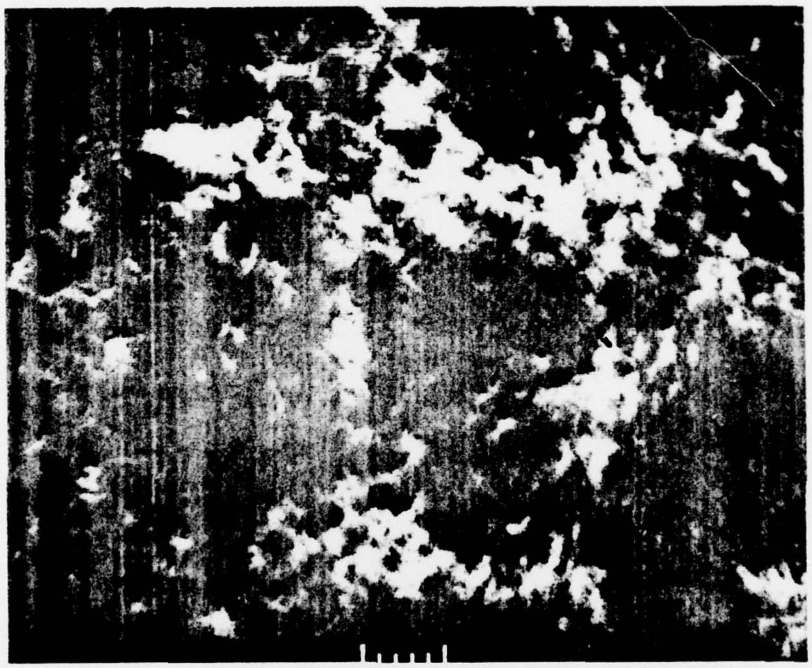

FIG. 2.—Magnetogram of the area outlined in Fig. 1. The tick marks along the bottom are at 1″ intervals.

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